New Near-Infrared Surface Brightness Fluctuation Models

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ABSTRACT

We present new theoretical models for surface brightness fluctuations in the near-infrared. We show the time evolution of near-infrared brightness fluctuation properties over large age and metallicity ranges, i.e., from 12 Myr to 16 Gyr, and from $Z/Z_\odot = 1/50$ to $Z/Z_\odot = 2.5$, for single age, single metallicity stellar populations. All the stellar models are followed from the zero age main sequence to the central carbon ignition for massive stars, or to the end of the thermally pulsing regime of the asymptotic giant branch phase for low and intermediate mass stars.

The new models are compared with observed near-infrared fluctuation absolute magnitudes and colours for a sample of Magellanic Cloud star clusters and Fornax Cluster galaxies. For star clusters younger than $\sim 3\,\mathrm{Gyr}$, the predicted near-infrared fluctuation properties are in a satisfactory agreement with observed ones over a wide range of stellar population metallicities. However, for older star clusters, the agreement between the observed and predicted near-IR brightness fluctuations depends on how the surface brightness absolute magnitudes are estimated. The computed set of models are not able to match the observed near-IR fluctuation absolute magnitudes and colours simultaneously. We argue that the observed discrepancies between the predicted and observed properties of old MC superclusters are more likely due to observational reasons.

Key words: stars: AGB – galaxies: star clusters – galaxies: stellar content – infrared: galaxies

1 INTRODUCTION

Over the last years, surface brightness fluctuations (SBFs) have been recognized as a powerful tool for providing accurate information on galaxy properties (Tonry, Ajhar, & Luppino 1990, Tonry & Schneider 1988, Blakeslee et al. 2001). SBFs constitute a reliable technique to determine cosmic distances to galaxies, out to galaxy clusters such as Fornax or Coma with typical uncertainties of the order of 10% or less (e.g. Tonry et al. 1990, Tonry et al. 1997, Liu & Graham 2001, Mei et al. 2001). In fact, using near-infrared (near-IR) data obtained by the Hubble Space Telescope, Jensen et al. (2001, 2003) have shown that the SBF technique can determine distances reliably out to $\sim 150\,\mathrm{Mpc}$ ($H_\circ = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). The usage of SBFs as a distance indicator requires that the bright end of the stellar luminosity function in galaxies is universal, or that the variation from galaxy to galaxy can be calibrated.

The problem of estimating the age and metallicity of stellar populations in galaxies is a highly controversial topic.

The sensitivity of SBFs to stellar age and metallicity offers an opportunity to investigate the unresolved stellar content of galaxies, and thus provide new clues into their star formation history as a complementary tool to canonical methods based on integrated magnitudes and colours, and spectral features. SBFs are a well-defined characteristic of any stellar system. As a consequence of the dependence of the SBFs on the second moment of the stellar luminosity function, they supply additional constraints on the properties of stellar systems that are not retrievable from the integrated luminosity. Near-IR SBFs are sensitive to the presence of bright and cool stars, and may therefore be used to detect the presence of intermediate age stellar populations in galaxies. In contrast with the optical SBFs, near-IR SBF magnitudes show a complex sensitivity to age and metallicity (Worthey 1993). The combination of near-IR SBF magnitudes and optical/near-IR integrated colours is suspected to lift significantly the age-metallicity degeneracy (Blakeslee et al. 2001; Liu et al. 2000).

Extensive observational and theoretical work has been

conducted to measure and to model the SBFs in the optical (e.g., Tonry et al. 1990, Worthey 1993, Liu et al. 2000, Blakeslee et al. 2001, Cantiello et al. 2003). However, the situation is completely different in the near-IR, whose observational windows have been, until recently, poorly exploited (Liu et al. 2002, Jansen et al. 2003). The scarcity of detailed near-IR SBF studies is due to the lack of both accurate empirical calibration and self-consistent models in the near-IR. The near-IR SBF signal is more sensitive to the presence of late-type giant stars than the integrated stellar population luminosity, i.e., the brightest few magnitudes of the stellar luminosity function dominate the near-IR SBF signal (Liu et al. 2000). So, the accuracy of near-IR SBF predictions depends strongly on the reliability of the stellar evolution ingredients used to model late stellar evolutionary phases. The inability of stellar population models to account correctly for stellar systems near-IR properties is due to (i) the lack of a reliable understanding of late stellar evolution phases, and (ii) difficulties in the modeling of broad molecular bands that dominate the near-IR spectra of late-type stars.

Mouhcine and collaborators have studied the spectrophotometric properties of stellar populations focusing on the most controversial predictions of stellar population synthesis models, i.e., the near-IR properties of intermediate age stellar populations (Mouhcine & Lançon 2002, Mouhcine et al. 2002, Mouhcine 2002, Mouhcine & Lançon 2003). The purpose of these models was to provide a global framework for the study of various observational aspects of evolved stars in intermediate age populations, ranging from their contribution to the integrated light to the statistical weights of their carbon-rich and oxygen-rich representatives. The theoretical predictions of the stellar population evolutionary models were extensively compared to observational constraints. The models were successful in reproducing a large variety of those constraints. The main step forward with these models is a better inclusion of the evolution of low and intermediate mass stars through a double-shell burning phase, known as the Thermally Pulsing Asymptotic Giant Branch (TP-AGB; see also Marigo et al. 2003 for another attempt to include TP-AGB in stellar population models).

Recently, González et al. (2004) have presented the near-infrared SBF measurements for a sample of Magellanic Clouds (MC hereafter) star clusters using the Second Incremental and All Sky Data releases of the Two Micron All Sky Survey (2MASS). This work opens up an opportunity of sharpening the capabilities of SBF measurements as diagnostics of unresolved stellar populations. The MC star clusters cover a wide range of ages, i.e., from a few Myr to more than 10 Gyr; on the other hand, they cover a narrow range of stellar metallicities, i.e., from $Z/Z_\odot \approx 1/30$ to $Z/Z_\odot \approx 0.5$. These properties of the clusters, combined with the predicted sensitivity of near-IR SBFs to age and metallicity, offer a unique way to disentangle the effects of age and metallicity on stellar population properties. On the other hand, the sensitivity of near-IR SBF signal to the details of stellar evolution provides an opportunity to constrain the accuracy of different ingredients of stellar population synthesis models. In this paper, we present new models of near-IR SBFs over a wide range of ages and metallicities for single-metallicity, single burst stellar populations, based

on the stellar populations synthesis models of Mouhcine & Lançon (2002).

The layout of this paper is as follows. In § 2, we outline the ingredients of the stellar population synthesis models. In § 3 we discuss the evolution of absolute near-IR fluctuation magnitudes for a large range of ages and metallicities, and compare the theoretical predictions to observed near-IR SBFs. Finally, in § 4 the results of the present work are summarised.

2   NEAR-INFRARED SURFACE BRIGHTNESS MODELS

The near-IR SBF models presented in this paper are based on the stellar population synthesis code described and tested observationally in Mouhcine & Lançon (2002, 2003). The code is designed to reproduce the near-infrared properties of both resolved and unresolved stellar populations, with an emphasis on intermediate age stellar populations. In this section, we describe briefly the main ingredients of the stellar population synthesis models, referring to the quoted papers for more details.

2.1   Single Stellar Population Models

The library of evolutionary tracks used in the population synthesis models is based on the models of Bressan et al. (1993) and Fagotto et al. (1994 a,b,c). We will refer to these sets as the Padova tracks hereafter. We include tracks with metallicities ranging from 1/50 to 2.5 times solar metallicity. The sets of tracks cover major stellar evolutionary phases: from the main sequence to the end of the early-AGB phase of low- and intermediate-mass stars, and to the central carbon ignition for massive stars. As pointed out earlier, the contribution of intermediate mass stars to near-IR SBFs is large. So, the accurate inclusion of the latest evolutionary phase of low and intermediate mass stars, through the luminous double-shell burning regime at the end of the AGB, i.e. TP-AGB, is crucial. The Padova tracks do not extend to the end of the TP-AGB phase. The extension of these tracks to cover the TP-AGB phase is needed. The evolution of low- and intermediate-mass through the TP-AGB evolutionary phase is followed using the so-called synthetic evolution modelling (Iben & Truran 1978; Renzini & Voli 1981). The inclusion of different processes affecting this stellar evolutionary phase (i.e., envelope burning, superwind, the third dredge-up) has been revealed to be crucial in order to match a variety of observational constraints (see Mouhcine & Lançon 2002). Only a few of the widely used single metallicity, single burst stellar population, i.e., simple stellar population (SSP hereafter) models, account for these processes with modern prescriptions that take into consideration the complex interplay between them (Marigo et al. 2003).

The initial conditions needed to calculate the evolutionary tracks of TP-AGB stars, i.e., the total mass (M), core mass (M_c), effective temperature (T_{eff}), luminosity (L), and envelope chemical abundances, are taken directly from Padova tracks for different masses and metallicities. The properties of TP-AGB stars are then allowed to evolve according to semi-analytical prescriptions (Wagenhuber & Groenewegen 1998). These prescriptions take into account

the effect of metallicity on the instantaneous properties of TP-AGB stars. The evolution of TP-AGB stars is stopped at the end of the AGB phase since their contribution to the optical/near-IR light is almost negligible once they evolve behind this phase. The calculations of stellar evolution through the TP-AGB phase are performed using a mixing length parameter $\alpha = 2$, Blöcker's (1995) mass loss prescription ($\dot{M} = 6.13 \, 10^{-4} \eta \, L^{4.2} T_{eff}^{-2} M^{-3.1}$, with a mass loss efficiency $\eta = 0.1$), dredge-up efficiency $\lambda = 0.75$, and the critical core mass to trigger the third dredge-up $M_c = 0.58 \, M_\odot$; such is a set of stellar parameters and prescriptions that reproduces fairly well various constraints on TP-AGB stars in the solar neighbourhood and nearby resolved galaxies.

A new set of stellar evolutionary models has been published recently by the Padova group that include several physical updates (Girardi et al. 2000). We have relied, however, on the Padova 1994 evolutionary tracks for the following reasons. The population synthesis code we are using to compute near-IR SBFs was built initially to study the properties of intermediate age populations, and thus to constrain the free parameters of TP-AGB star models (see Mouhcine & Lançon 2002 for more details). This was done using old Padova tracks as initial conditions to the TP-AGB evolution models. The derived values of the free parameters of TP-AGB evolution models might not be valid if different evolutionary tracks and initial conditions for TP-AGB star models are used; in this case, the agreement between predicted and observed intermediate age stellar populations cannot be guaranteed. On the other hand, the old Padova evolutionary tracks appear to be more consistent with observational constraints than the new set of Padova tracks (e.g., Bruzual & Charlot 2003; see also González et al. 2004).

Stellar libraries are needed to assign spectral energy distributions to the stars of a synthetic population. For stars evolving through evolutionary phases other than the TP-AGB, we have used the theoretical stellar atmospheres of Kurucz (see Kurucz, 1979), Fluks et al. (1994) and Bessell et al. (1989, 1991), as collected and re-calibrated by Lejeune et al. (1997, 1998). This library has the advantage of covering a broad range of temperatures, gravities and metallicities.

The Basel group has published recently a semi-empirical stellar spectral library that is calibrated to non-solar metallicities (Westera et al. 2002). Nevertheless, we have used the library of Lejeune et al. (1997, 1998), rather than that of Westera et al. (2002), for reasons that have to do with the available calibration data. Given the available calibration data, i.e., globular cluster colour-magnitude diagrams and empirical colour-effective temperature relations, Westera et al. (2002) have concluded that it is impossible to establish a unique calibration of UBVRIJHKL stellar colours in terms of stellar metallicity that is consistent simultaneously with all the available data sets. On the other hand, the data that would allow a consistent calibration of the relationship between stellar near-IR colours and effective temperatures are extremely scarce. More data has to be collected to improve the quality of the calibration in the near-IR (see Westera et al. 2002 for a detailed discussion). On the other hand, Bruzual & Charlot (2003) have shown that a combination of the Padova 1994 stellar evolutionary tracks with the Westera et al. (2002) library provides satisfactory fits to observed colour-magnitude diagrams of star clusters of dif-

ferent ages and metallicities. However, the comparison was performed mainly in optical bands. In addition, the evolution of near-IR fluctuation colours for old stellar populations as predicted by González et al. (2004), who used the Westera et al. (2002) library, shows a behaviour which is not entirely consistent with the well established fact that near-IR colours of RGB stars get redder as their initial metallicity increases (see Sect. 3.1 for more details). Theoretical and observational work is needed in order to understand if the discrepancies observed by Westera et al. (2002) are due to the colour-temperature relations, to the isochrones, or both.

The spectrophotometric properties of TP-AGB stars are different from those of giant stars. Their extended and cool atmospheres lead to the formation of deep and specific spectral absorption bands. The photometric properties of oxygen-rich and carbon-rich stars TP-AGB stars are different; as an example, carbon stars show redder (H-K) colours than oxygen-rich TP-AGB stars at a given (J-H) colour. The dichotomy between carbon-rich and oxygen-rich TP-AGB stars is rarely considered in SSP models available in the literature. To account for TP-AGB star properties, we used the empirical library of average TP-AGB star spectra of Lançon & Mouhcine (2002).

It is extremely difficult to estimate the effective temperature and the metallicity of variable TP-AGB stars. The uncertainties in current models of both stellar interiors and atmospheres of TP-AGB stars make it difficult to estimate reliably the fundamental physical parameters of these stars. Optical/near-infrared colours and narrow band indices are usually used as effective temperature indicators for M type TP-AGB stars. Note that narrow band indices show a larger scatter than optical/near-infrared colours due to the sensitivity of molecular bands to the structure of the outer atmosphere, which is affected by pulsation (Bessell et al. 1989; Alvarez & Plez 1998; Lançon & Wood 2000). The effects of metallicity on the JHK spectra of M type TP-AGB stars are unclear. At a low spectral resolution, the shapes of JHK spectral features of stars in the Large and Small Magellanic Clouds (Lançon & Wood 2000) and near the Galactic Centre (Schultheis et al 2002) show no sizeable systematic differences with thOse observed for stars in the Solar Neighbourhood. However, the L-band spectral features of M type TP-AGB stars seem to depend on the metallicity (Matasuura et al. 2005).

For M type TP-AGB spectra, two different effective temperature scales could be used. The first one assumes that variable TP-AGB stars may have the same effective temperature scale as static giant stars; the second one considers that the effective temperatures of variable TP-AGBs may differ from those of static giants. The shapes of the spectral features of stellar populations dominated by oxygen-rich stars depend strongly on the effective temperature scale of these stars. However, the adopted temperature scale has almost no effect on the evolution of integrated broadband photometry of stellar populations (see Mouhcine et al. 2002 for a detailed discussion). The effect of metallicity on oxygen-rich TP-AGB star spectra, at a given effective temperature, is taken into account to first order, by using a metallicity-dependent effective temperature scale, i.e., the relationship between effective temperature and (I-K) of Bessell et al. (1991).

Theoretical modelling of carbon star spectra shows that

the spectral features of carbon stars depend, in addition to the effective temperature and metallicity, on the C/O ratio, the ^{13}C/^{12}C ratio, and the microturbulence (Gautshy-Loidl 2001). On the other hand, the C/O ratio depends on the metallicity and the evolutionary status of the stars along the TP-AGB sequence (Marigo 2002; Mouhcine & Lançon 2003). Despite the relative success of synthetic spectra to account for the shape of spectral energy distributions of carbon stars, we note that the effects of different parameters on different spectral features are degenerate, making it difficult to derive fundamental stellar parameters that are consistent from the stellar evolution point of view (see Loidl et al. 2001, and Lancon & Mouhcine 2002 for a detailed discussion). Observationally, the JHKL spectrophotometric properties of carbon stars show complicated behaviour, i.e., some spectral indices, such as the (J-H) colour and the HCN equivalent width, decrease with metallicity, while others, such as the (H-K) colour and the C_2H_2 equivalent width, cover at low metallicities similar ranges than what is observed for carbon stars in the Solar Neighbourhood (Östlin & Mouhcine 2005, Matasuura et al. 2005). Similarly to what was done for oxygen-rich TP-AGB star spectra, the effect of metallicity on carbon star spectra is taken into account to first order, by using a metallicity-dependent effective temperature scale, i.e., the relationship between effective temperature and (R-H) of Loidl et al. (2001).

Once the physical ingredients describing different stellar evolutionary phases, and the recipe used to estimate the magnitude and colours of the stars are specified, the only free parameters of a SSP model are those that describe the initial mass function (IMF). For the rest of the paper we use the standard Salpeter (1955) IMF. The adopted lower and upper mass cut-offs are $M_{min} = 0.1\,M_\odot$ and $M_{max} = 120\,M_\odot$. The Salpeter IMF is not valid down to $0.1\,M_\odot$ (e.g. Salpeter 1955, Scalo 1986, Kroupa 2001), although the IMF shape at $M_{init} \lesssim 0.6\,M_\odot$ appears to not have large effects on SBF predictions (see Blakeslee et al. 1999 for a detailed discussion).

2.2 Computing Surface Brightness Models

We compute integrated and fluctuation magnitudes and colours, through the 2MASS near–IR filters, of single–burst stellar populations. In order to cover the range of typical ages and metallicities of stellar populations in galaxies and globular clusters, we compute the SBF absolute magnitudes and colours for ages ranging from 12 Myr to 16 Gyr and initial stellar metallicities of $Z/Z_\odot = 1/50, 1/5, 1/2.5, 1$, and 2.5.

The fluctuation luminosity is defined as the ratio of the second moment of the luminosity function to its first moment, i.e., the integrated luminosity. This can be expressed with the following equation:

$$\bar{L} \equiv \frac{\Sigma n_i {L_i}^2}{\Sigma n_i L_i}, \qquad (1)$$

where n_i is the number of stars of type i and luminosity L_i. Bright stars are the main contributors to the numerator, while faint stars contribute significantly to the denominator. The numerator of eq. 1 is calculated by summing L^2 over all stellar types in the models, i.e., $n_i \neq 1$ in general. The denominator of eq. 1 and the integrated quantities are obtained also by summing the L of all types of star at each wavelength.

3 RESULTS

The least ambiguous test for SSP models is to compare there predictions to the observed properties of globular clusters since they are thought to be the best observational counterpart of theoretical SSPs. In this section, we present a comparison between the predicted and observed evolution of near-IR SBFs as a function of age and metallicity. The corresponding numerical data of the models presented in this paper are listed in Table 1.

González et al. (2004) presented near-IR SBFs for a sample of 191 MC star clusters. In order to reduce stochastic effects due to small numbers of stars on fast evolutionary phases, e.g., Red Giant Branch (RGB) and AGB, near-IR SBFs for *superclusters* were built by coadding clusters in the Elson & Fall (1985, 1988) sample that have the same SWB class (Searle, Wilkinson, & Bagnuolo 1980). Eight superclusters were thus assembled, one for each of the seven different SWB classes (Searle et al. 1980), plus one "pre-SWB-class" supercluster. The SWB classification is a smooth sequence of increasing age and decreasing metallicity. Ages and metallicities of the superclusters were taken from Frogel et al. (1990), with the following exceptions: the metallicity of MC superclusters with SWB type I and II were taken from Cohen (1982); in the case of the youngest (pre-SWB) supercluster, its metallicity was extrapolated from Fig. 2 of Cohen (1982), and an age of 2.4 Myr was assumed. The MC supercluster ages from Frogel et al. (1990) have been corrected to the LMC distance modulus $(m - M)_\circ = 18.5$, used by González et al. (2004).

Unfortunately, no MC globular cluster with a solar or a super-solar metallicity is known. One needs to look at early-type galaxies to test the accuracy of SBF predictions for metal-rich stellar populations. For this purpose, we use the near-IR SBF measurements for a sample of Fornax Cluster early-type galaxies from Liu et al. (2002) and Jensen et al. (2003). Ages and metallicities for the sample galaxies have been taken from Kuntschner (1998), and are based on the analysis of optical spectral features. It is worth to mention that both Fornax Cluster galaxy ages and metallicities are luminosity weighted.
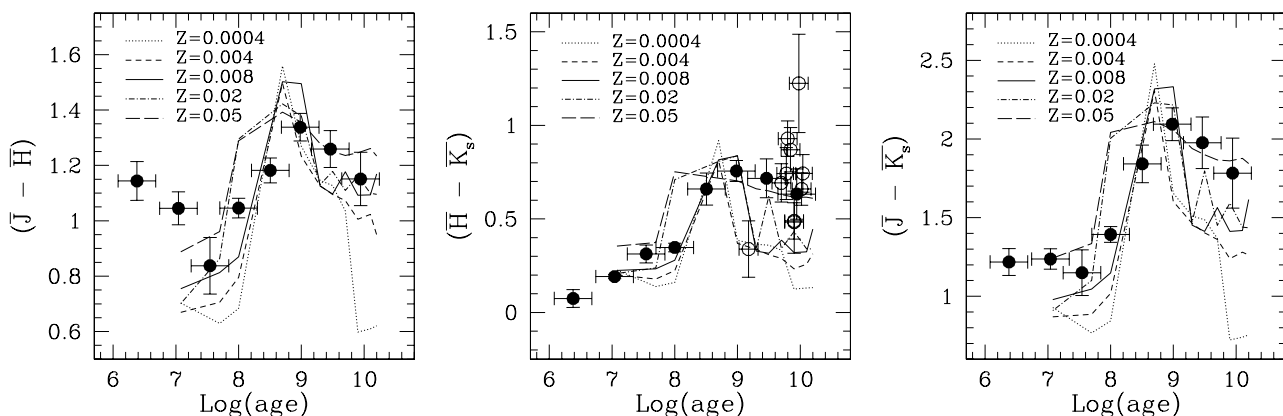
3.1 Fluctuations versus Age

3.1.1 Comparison with observational data

Fig. 1 shows a comparison between the predicted and observed evolution of near-IR absolute fluctuation magnitudes as a function of stellar population age. MC globular cluster are shown as filled circles,[⋆] and Fornax Cluster galaxies as open circles. SSP models with different metallicities are shown with different lines as indicated in each panel. The data show that the near-IR absolute fluctuation magnitudes get fainter as the superclusters age. The new near-IR

[⋆] SBF magnitudes for the supercluster class SWB I are about 0.15 mag brighter, and those for class SWB II about 0.05 mag fainter than formerly published –González, Liu, & Bruzual (2005).
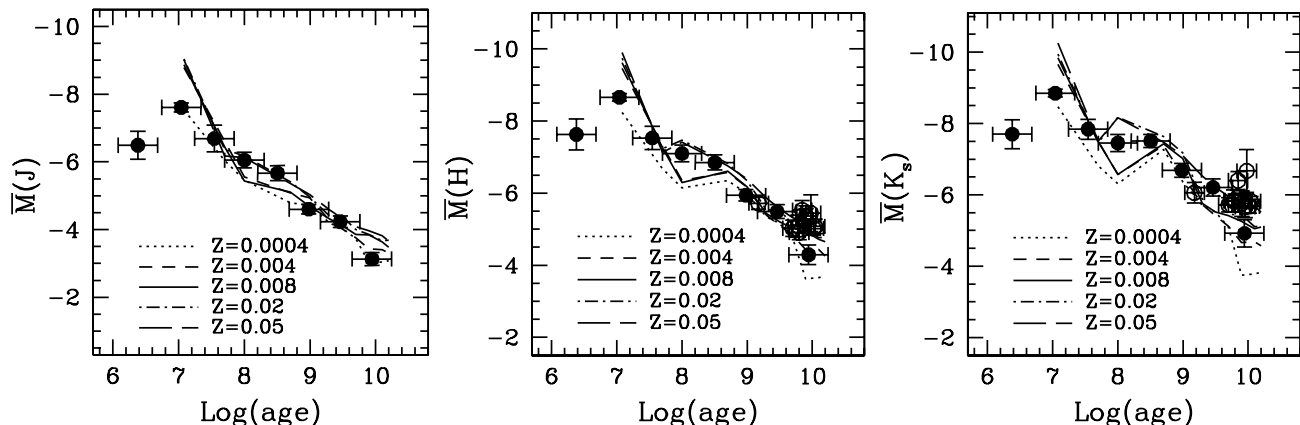
Figure 1. Comparison of J-band (*left*), H-band (*middle*), and K_s-band (*right*) SBF magnitudes versus age with the predictions of stellar population synthesis models. Filled circles show the MC supercluster SBF measurements, open circles show those derived for Fornax Cluster galaxies.

Figure 2. Comparison of fluctuation colours $(\bar{J} - \bar{H})$ (*left*), $(\bar{H} - \bar{K}_s)$ (*middle*), and $(\bar{J} - \bar{K}_s)$ (*right*) versus age with the predictions of stellar population synthesis models. Models and symbols are the same as in Fig. 1.

SBF models agree remarkably well with the observed trend. The figure shows clearly that the distance modulus to the MCs derived from the predicted near-IR absolute fluctuation magnitudes is in a good agreement with the recent determinations from other distance indicators. Note that the good agreement between observed and predicted trends is relevant considering that the set of free parameters used to describe the evolution of TP-AGB stars has not been tuned to reproduce the observed fluctuation magnitudes. This confirms the reliability of the adopted theoretical tool to model the evolution of TP-AGB stars, and then the stellar population models used to predict near-IR SBFs.

For stellar populations older than 100 Myr, the evolution of low- and intermediate-mass stars through the red giant branch and the AGB regulates the evolution of near-IR spectrophotometric properties and SBF signal. The monotonic dimming of near-IR fluctuation magnitudes in these stellar populations is related to the evolution of late-type giant star content. As a stellar population ages, the mass of stars fueling the evolution of near-IR SBF signal, i.e., AGB stars for ages younger than $\sim$ 1.5 Gyr, and red giant stars for older ages, decreases. At a fixed metallicity, the average luminosity of stars on the red giant branch decreases with

a stellar population age (see González et al. [2004] for a detailed discussion). On the other hand, SSP models show, at a fixed age, brighter absolute near-IR fluctuation magnitudes at higher stellar population metallicity. Due to opacity effects, more metal-rich stars are redder than their metal-poor counterparts and, hence, are brighter in the near-IR.

On top of the overall trend of near-IR SBFs dimming as stellar populations age, a short migration of near-IR fluctuations to brighter magnitudes is predicted for stellar populations between 0.5 and $\sim$ 1.5 Gyr. The predicted migration gets brighter going from $J-$band to $K-$band. This behaviour is due to a temporary predominance of bright and cool carbon stars. As the production rate of such stars decreases significantly at high metallicity, the migration is virtually absent for super-solar stellar population models.

For stellar population studies, although the fluctuation absolute magnitudes can be used to set constraints on the properties of the stellar populations, the fluctuation colours are, in principle, more useful, as they do not depend on the distance determinations. It is therefore interesting to investigate their evolution and sensitivity to stellar population properties. In Fig. 2 we show a comparison between the observed and predicted temporal evolution of near-IR fluctua-
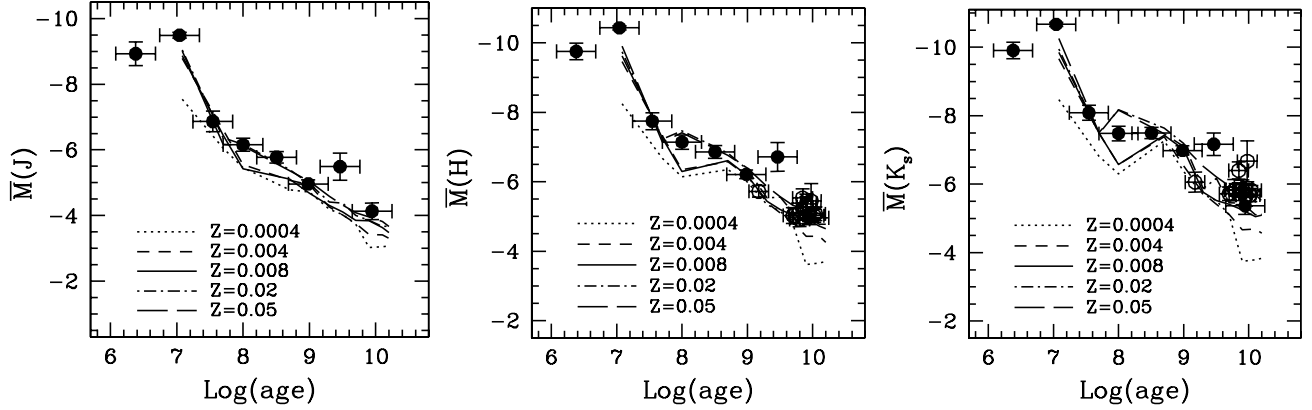
Figure 3. Similar to Fig. 1, but the observed MC near-IR SBF magnitudes are estimated including all point sources in the 2MASS Point Source Catalog within 1′ from the centres of the superclusters (see text for more details).
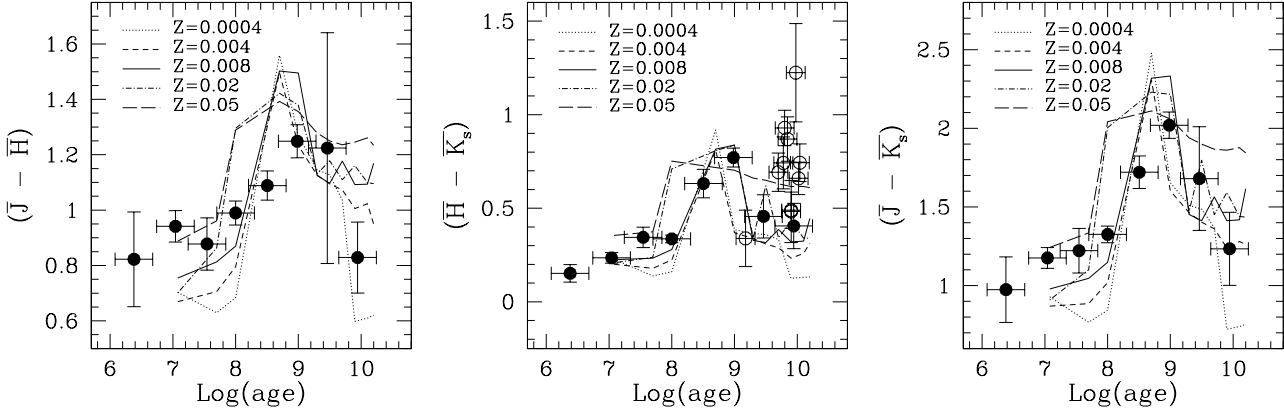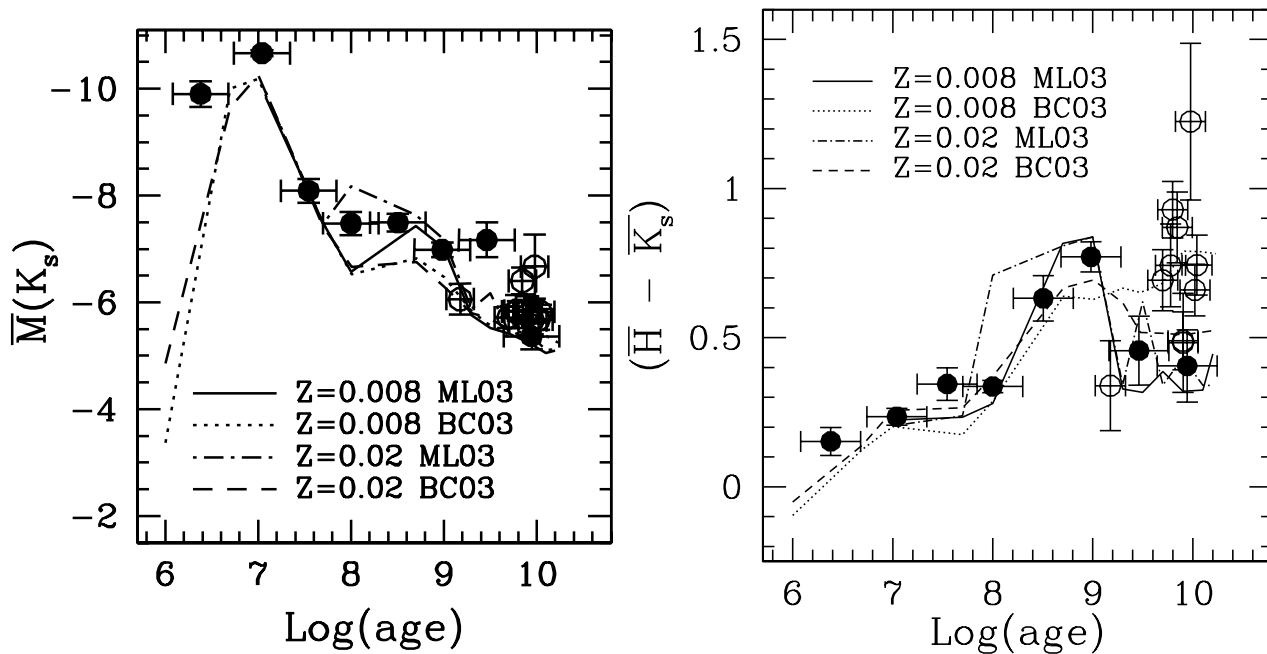

Figure 4. Similar to Fig. 2, but the observed MC near-IR SBF magnitudes are estimated including all point sources in the 2MASS Point Source Catalog within 1′ from the centres of the superclusters (see text for more details). The match between the predictions and the observations for old stellar populations, i.e., MCs with SWB type VI and VII, is very good.

tion colours. Different symbols and lines are the same as in Fig. 1.

The new SSP models show that near-IR fluctuation colours get redder until they reach a maximum at $0.7 - 1.0$ Gyr, depending slightly on metallicity. Subsequently, the evolution of near-IR fluctuation colours reverses and they get bluer up to an age of $1.5 - 2.0$ Gyr. From then on, except for the most metal-poor models $(Z/Z_\odot = 1/50)$, near-IR fluctuation colours of older stellar populations are almost constant over several Gyrs. This is not completely unexpected. The predicted evolution is quantitatively similar to what is anticipated for near-IR integrated colours (Mouhcine & Lançon 2003). The only difference is that, for sub-solar SSP models and for a given age, integrated colours get redder for higher metallicities, while the migration of near-IR fluctuation colours to the red is sharper for metal-poor stellar populations. The most metal-poor SSP model shows the reddest near-IR fluctuation colours at the end of this evolutionary phase. The predicted sensitivity of near-IR fluctuation colours to metallicity is due to (i) a larger sensitivity of near-IR SBF signal to the presence of bright and cool AGB stars, and (ii) a higher carbon stars formation efficiency at low metallicity. The match between the predicted

near-IR fluctuation colours and the observed ones for MC superclusters of SWB types lower than V is good. The observed abrupt jump of near-IR fluctuation colours to the red for stellar populations between 100 Myr and 1 Gyr is well matched by the predicted evolution.

The observed near-IR fluctuation colours for MC superclusters of SWB types VI and VII are surprisingly redder than the predicted fluctuation colours given their metallicities, i.e., $0.008 \lesssim Z \lesssim 0.0006$. The near-IR light budget of stellar populations older than ~ 3 Gyr, i.e., globular clusters of SWB type VI or larger, is dominated by red giant stars; the physics of these stars is well understood to the level of detail that matters for stellar population synthesis models, and its effects on integrated properties of stellar populations are well understood. Changing the SWB class-age transformation does not solve the discrepancy between the predicted (blue) and observed (red) near-IR fluctuation colours. It is worth to mention that for both superclusters, a good agreement is found between observed and predicted integrated colours given their ages and metallicities. It is hard to come up with any physical explanation for the observed red fluctuation colours of the two oldest MC star clusters. One possible solution to the discrepancy between the observed red

Figure 5. Comparison of the temporal evolution of K_s-band SBF magnitude (*left*) and fluctuation colour ($\bar{J} - \bar{H}$) (*right*), for both solar and $Z/Z_\odot = 1/2.5$ metallicities. The observed MC near-IR SBF magnitudes are estimated including all point sources in the 2MASS Point source Catalog within $1'$ from the centres of the superclusters (see text for more details). *Solid and dotted–short dashed lines*: models used in this paper, based on isochrones of Mouhcine & Lançon (2003; ML03). *Dotted and dashed lines*: models used in Gonzàlez et al (2004), based on isochrones of Bruzual & Charlot (2003; BC03).

and the predicted blue fluctuations for metal-poor and old stellar populations is that the measured near-IR SBFs of the two oldest MC superclusters, i.e., SWB types VI and VII, are not well determined for observational reasons. The bright end of the RGB sequences of MC superclusters of SWB types VI and VII is poorly populated (see figure 3 of González et al. 2004). A possible contamination of the upper bright end of the red giant branch by foreground red stars might affect strongly the measured near-IR SBF magnitudes given their sensitivity to the presence of red stars.

A second potential source of uncertainty is the methodology used by González et al. (2004) to estimate near-IR SBF magnitudes for MC star clusters. They have eliminated all point sources with dubious photometry using the flags from the 2MASS Point Source Catalog. Table 2 lists the near-IR fluctuation absolute magnitudes for the MC superclusters when all point sources within a radius of $1'$ from the centres of the superclusters are included, independently of the 2MASS Point Source Catalog flags. A comparison with the near-IR SBF absolute magnitudes listed in Table 4 of González et al. (2004) and revised in Table 1 of González et al. (2005) shows that the near-IR SBF absolute magnitudes of some of the MC superclusters, i.e., Pre-SWB, I, VI, and (albeit to a lesser extent and mostly in the J-band) VII, are significantly affected by the procedure used to select the members of the superclusters, and by their photometric quality. Fig. 3 shows a comparison between the predicted evolution of near-IR fluctuation absolute magnitudes, and observed ones for the MC superclusters as listed in Table 2.

The systematic errors incurred when deriving SBF magnitudes of resolved star clusters have been amply discussed

in González et al. (2004; see their Sect. 4.2, and Fig. 5). The two main issues involved are the sky level and, notoriously, the crowding. Through the blending of sources, crowding will make SBF magnitudes brighter. Crowding is most likely in small areas with relatively bright stars. Consequently, the central regions of star clusters are always the most vulnerable to crowding and, if the problem indeed exists, the fluctuation magnitudes should in principle be brighter there than when including larger radii.

The analysis by González et al. (2004),[†] updated to take into account the corrected data of SWB classes I and II (González et al. 2005), indicates that in all but the Pre-SWB and type I superclusters, when using only stars with good photometry, fluctuation magnitudes in the central regions are actually fainter, not brighter, than when considering whole regions with $0'' \leq r \leq 60''$. That is, while the Pre-SWB and type I superclusters show the expected bias, the other ones display the effects of crowding in their centers only indirectly, since blended sources are discarded via the photometric flags and hence SBFs appear fainter. When carrying out the analysis with all the stars, the fluctuation magnitudes for the whole regions between $0''$ and $60''$ change significantly only for the superclusters types Pre-SWB, I, and VI. And, tellingly, only for those three superclusters the fluctuations for the centralmost regions are now (when all

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[†] The analysis consisted in the comparison of fluctuation magnitudes and colours calculated in different regions of the MC superclusters and, especially, between values obtained in the central $0''$ to $20''$ and from the whole region encompassed between $0''$ and $60''$.

sources are considered) brighter than for the whole regions between $0''$ and $60''$. The implication is that the Pre-SWB and type I superclusters suffer from a crowding so severe that it leaves its expected, direct imprint even when taking into account only sources with nominally good photometric measurements. On the other hand, for supercluster type VI, crowding is only a problem when all point sources are included. Ideally, one should derive fluctuation magnitudes from uncrowded regions, but in the case of these data the 2MASS flags have been useful to correct the effects of mild crowding. Unfortunately, we have to conclude that the measurements for the superclusters Pre-SWB and type I have to be taken with caution until data with better spatial resolution can be obtained. In the case of the supercluster type VII, even when it does not appear to be badly crowded, the brightest end of old superclusters is poorly populated, so adding or substracting a few bright stars could have disproportionately large effects for statistical reasons. Aside from crowding, this ingredient could also be at play in supercluster type VI.

Interestingly, fluctuation colours do not seem to be affected by crowding. Fig. 4 shows a comparison between the predicted evolution of near-IR fluctuation colours, and those estimated for the MC superclusters using the near-IR SBF absolute magnitudes listed in Table 2. For regions within $1'$ of their centres and for all superclusters, the empirical values derived from the observations including all sources are consistent within 1 to 2-σ errors with those obtained when only sources with good photometry are taken into account. To explain the simultaneous observations that fluctuation magnitudes are sensitive to crowding, while fluctuation colours do not seem to be, it is possible to suppose that if crowding is similar at two wavelengths, its effect on the fluctuation magnitudes will cancel out when calculating a colour. Alternatively, the colour of two blended stars could be dominated by the bright star, and yet the fainter star would contribute significantly to the measured brightness. This would be similar to an effect that has a role in the skewed shape of the luminosity distribution of main sequence stars with a given spectral type (see, e.g., Binney & Merrifield 1998). In that case, the departure from the Gaussian shape is produced at least in part by unresolved binaries in the sample. The spectral classification is likely to be based on the brighter star, while both stars will contribute to the measured brightness. In the case of fluctuation measurements, blended stars are not real binaries, but their colour (like the spectral class of main sequence binaries) might be dominated by the bright star, while the fainter star will still contribute significantly to the detected flux.

Finally, Fig. 4 suggests that there might be a better match between predicted and observed near-IR colours when all sources, regardless of their photometric quality, are included. We caution, however, against giving too much weight to this result. For example, although the very crowded Pre-SWB and SWB type I superclusters, as well as the mildy crowded type VI supercluster, move in the *right* direction, however within the errors with respect to the values estimated without point sources with faulty photometry, for $(\bar{J} - \bar{H})$ and $(\bar{J} - \bar{K}_s)$ the overall impression of improvement hinges mostly on the point for SWB VII supercluster. The discussion in this section points towards the conclusion that the estimated near-IR SBF magnitudes of the two

youngest and the two oldest MC superclusters by González et al. (2004) might be affected by important observational uncertainties. One could perform simulations to test our hypotheses on the resilience of fluctuation colours to crowding but, mainly, it would be definitely worthwhile to reobserve very young and very old MC star clusters in the near-IR with better spatial resolution and sky stability, in order to determine properly their near-IR SBF magnitudes.

The agreement between observed near-IR fluctuation colours of Fornax Cluster galaxies and predicted ones for similar ages and metallicities is satisfactory, given the SBF measurement errors. However, a few early-type galaxies show much redder colours than what is predicted by the most metal-rich SSP model. Note that observed near-IR integrated colours of Fornax Cluster galaxies agree well with the predictions of SSP models given their ages and metallicities. The star formation histories of Fornax Cluster galaxies are likely different from the single burst history assumed in the models, and intermediate age stellar populations can exist (e.g., Bower et al. 1998). Various evidence suggests that early-type galaxies have had more complex star formation histories, and may contain a mixture of stellar populations with different ages and metallicities. The modelling of the effects of complex star formation history on the evolution of near-IR fluctuation colours is beyond the scope of this paper. Liu et al. (2002) have shown that recent star formation events on the top of an old stellar population are suspected to produce a scatter of near-IR fluctuations properties. An interesting prediction is that after few Gyr, when the effect of a recent star formation event on integrated colours almost vanishes and these become typical of old stellar populations, a sizeable signature of burst remains on the near-IR fluctuation properties. If a fraction of the galaxy stellar mass was formed in the last few Gyr, it can produce a significant spread of near-IR SBFs, depending on the mass fraction involved in the burst and its metallicity. This might explain why observed integrated colours of Fornax cluster galaxies are well reproduced while some Fornax cluster galaxies show redder near-IR fluctuation colours than the reddest models. The observed discrepancy might indicate that the single burst model is inappropriate to model their star formation histories.

3.1.2 *Comparison with theoretical predictions*

González et al. (2004) have calculated near-IR SBF magnitudes and fluctuation colours for single burst stellar populations using Bruzual & Charlot (2003) isochrones over similar ranges of age and metallicity than what is presented in this paper. Fig. 5 displays a comparison between the predictions of the temporal evolution of K_s-band SBF magnitude and $(\bar{H} - \bar{K}_s)$ fluctuation colour based respectively on Bruzual & Charlot (2003) and Mouhcine & Lançon (2003) isochrones. Also plotted are the observed near-IR SBF magnitudes and fluctuation colours of MC superclusters estimated using all point sources detected within $1'$ from the centres of the superclusters. Both sets of theoretical predictions are shown for Z=0.02, and Z=0.008 metallicities. Other sets of theoretical predictions of near-IR SBF magnitudes of simple stellar populations are available in the literature; however, they generally use Bruzual & Charlot (2003) isochrones or one of their earlier versions (Liu et al. 2001, Mei et al. 2001),

or they are computed for old stellar populations only, i.e., they do not cover the stellar population age range spanned by the MC superclusters (e.g., Worthey 1993, Blakeslee et al. 2001, Cantiello et al. 2003).

The figure shows that both sets of models predict qualitatively similar evolution of K_s-band SBF magnitude over the age range comprised by them, i.e., the K_s-band SBF magnitude gets fainter as a stellar population ages. However, sizeable differences between the two sets of predictions are apparent. For stellar populations between 100 Myr and 1.5 Gyr, the models based on Mouhcine & Lançon (2003) isochrones predict a jump of the K_s-band SBFs to brighter magnitudes, and that this jump is metallicity dependent. Conversely, the models based on Bruzual & Charlot (2003) isochrones show a weak brightening of the K_s-band SBF magnitude. The predicted K_s-band SBF magnitudes by González et al. (2004) at the age of MC superclusters of SWB types III and IV, for which the SBF measurements are not affected seriously by observational uncertainties, are fainter than the observed ones by $0.5 - 1$ magnitude. The presence of AGB stars in the stellar populations during this age interval does not translate into noticeable changes in the near-IR light in these models. To reproduce the K_s-band SBF magnitudes observed for the MC superclusters within this age range using González et al. (2004) models, a super-solar metallicity is needed, i.e., $Z/Z_\odot = 2.5$, much larger than the mean metallicity of MC star clusters of these ages ($Z/Z_\odot \approx 1/2$). To model the evolution of intermediate mass stars through the TP-AGB phase, Bruzual & Charlot (2003) have used the TP-AGB lifetimes published by Vassiliadis & Wood (1993). The TP-AGB lifetimes used in Mouhcine & Lançon (2003) stellar population synthesis models are larger than those of Vassiliadis & Wood (1993). The total number of TP-AGB stars present in a stellar population at a given age is directly proportional to the TP-AGB lifetime of the turn-off star at this age (e.g., Renzini & Buzzoni 1986; Mouhcine & Lançon 2002). So, shorter lifetimes underestimate the light budget of the TP-AGB star population, and lead to predict faint near-IR SBF magnitudes.

The comparison of the predicted temporal evolution of $(\bar{H} - \bar{K}_s)$ fluctuation colour by both sets of stellar population synthesis models, shown in the right panel of Fig. 5, again display noticeable differences. The most striking one is that, while models with Z=0.02 and Z=0.008 based on Mouhcine & Lançon (2003) isochrones follow a similar qualitative evolution (i.e., they redden with age up to ~ 1 Gyr, get bluer later on up to ~ 2 Gyr, and keep constant fluctuation colours for older stellar populations), the models based on Bruzual & Charlot (2003) isochrones differ between them. For this set, the solar metallicity model shows a qualitative bahaviour similar to what of our models; however, their Z=0.008 model predicts that the $(\bar{H}-\bar{K}_s)$ fluctuation colour gets redder as the stellar population ages. The result is that, for older stellar populations, the predicted $(\bar{H} - \bar{K}_s)$ fluctuation colours are redder for Z=0.008 than for solar metallicity. Note that the predicted $(\bar{H} - \bar{K}_s)$ fluctuation colour by González et al. (2004) for old stellar populations with a super-solar metallicity, i.e., Z=0.05, are also bluer than these of Z=0.008 model. This is the opposite of what is anticipated using Mouhcine & Lançon (2003) isochrones. For these models, the predicted $(\bar{H} - \bar{K}_s)$ fluctuation colours of old stellar populations with Z=0.008 are as red as what is observed

for Fornax Cluster galaxies, for which the mean metallicity is super-solar on average. The scaling of $(\bar{H} - \bar{K}_s)$ with metallicity for old stellar populations predicted by González et al (2004) cannot be explained by the presence of carbon stars, for which the formation efficiency is higer at low metallicity. The near-IR properties of stellar populations older than a few Gyrs are dominated by RGB stars. These stars show redder near-IR colours as their initial metallicities increase. Both the isochrones used by González et al. (2004) and the Mouhcine & Lançon (2003) isochrones are constructed using the same set of stellar tracks, for evolutionary stages earlier than the TP-AGB phase for intermediate and low mass stars. The only remaining potential source of the discrepancies observed between their predicted fluctuation colours is the use of different stellar libraries to transform the isochrones from theoretical diagrams to observed ones. Mouhcine & Lançon (2003) used the Lejeune et al. (1997, 1998) stellar spectral library, while Bruzual & Charlot (2003) used the library of Westera et al (2002).

The larger amplitude of the jump toward the red of $(\bar{H} - \bar{K}_s)$ for stellar populations younger than ~ 1 Gyr predicted by models based on Mouhcine & Lançon (2003) isochrones is due to the larger TP-AGB evolutionary phase lifetimes used. The jump of near-IR fluctuation colours to the red for stellar populations between ~ 0.1 Gyr and ~ 1.5 Gyr, i.e., when the near-IR light is dominated by TP-AGB stars, as predicted by González et al. (2004) does not show a large sensitivity to stellar population metallicity, even though metal-rich stellar populations do show redder fluctuation colours than metal-poor ones (see figure 9 of González et al. 2004). This contrasts with the predictions presented in this paper, where the jump to the red of near-IR fluctuation colours is sharper for metal-poor stellar populations as discussed above. The disagreement is due to the fact that Bruzual & Charlot (2003) do not take into account the sensitivity of carbon star formation rate to metallicity for metal-poor stars.

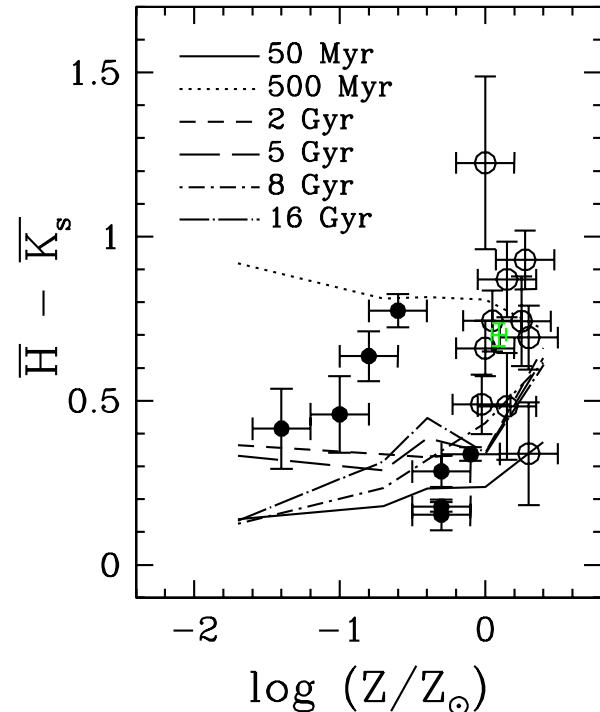### 3.2 Fluctuations versus Metallicity

In this section, we compare the predicted and observed relationships between fluctuation magnitudes and colours, and stellar population metallicity.

Fig. 6 shows the evolution of J-band, H-band, and K_s-band absolute fluctuation magnitudes respectively for MC superclusters and Fornax Cluster galaxies as a function of metallicity. Symbols are the same as in Fig. 1. MC supercluster fluctuation magnitudes are estimated using all point sources within $1'$ from the centres of the superclusters. Different lines connect SSP models with different metallicities, but with similar age. The agreement of the predicted relationships between near-IR SBF magnitudes and stellar population metallicity with the observed ones for MC superclusters, given their age, is satisfactory. The ages assigned to Fornax Cluster galaxies through their locations in the $M(\bar{H})$ vs. $\log(Z/Z_\odot)$ diagram, i.e., ages older than ~ 2 Gyr, are consistent with the age range of Kuntschner (1998). However, few Fornax Cluster galaxies show much brighter K_s-band SBF magnitudes than those of metal-rich stellar populations older than ~ 2 Gyr. The K_s-band SBF magnitude is probably more sensitive to recent star formation events than bluer passbands.

The SSPs models show, independently of stellar population metallicity, that older stellar populations display fainter near-IR fluctuation absolute magnitudes. The ability to assign an age to a stellar population, given its near-IR absolute fluctuation magnitudes, decreases with age, independently of metallicity. The short migration of K_s-band fluctuation absolute magnitude to brighter magnitudes is clear, i.e., the 500 Myr old SSP models are as bright as the 50 Myr old SSP models. The figure shows that the sensitivity of near-IR fluctuation magnitudes to stellar metallicity, at a given age, increases as one goes from J-band to K_s-band, with fluctuation magnitudes in J-band showing only a weak dependency on metallicity. This behaviour does not depend on age, at least in the range investigated in this work; moreover, such behaviour is expected. It is suspected that the evolution of SSP model properties in a filter around J-band is virtually independent of metallicity; the evolution of SSP properties reverses there, going from optical to near-IR wavelengths (Worthey 1994, Mouhcine & Lançon 2003). This suggests that J-band fluctuation magnitudes may be used as distance indicators, independently of galaxy metallicity. On the other hand, due to the sensitivity of K_s-band fluctuation magnitudes to metallicity, they may be used as a stellar population tracer. Coupled with their high luminosity, the predicted evolution of near-IR fluctuation absolute magnitudes supports the increasing number of SBF work in these bands.

Fig. 7 shows a comparison between the observed and predicted relationship of $(\bar{H} - \bar{K}_s)$ fluctuation colour and stellar population metallicity, for MC superclusters and Fornax Cluster galaxies. MC supercluster fluctuation colours are estimated using all point sources within $1'$ from the centres of the superclusters. Symbols and lines are the same as in Fig. 6. The observed $(\bar{H} - \bar{K}_s)$ fluctuation colours for MC superclusters agree well the predicted ones given their ages and metallicities. As discussed in section 3.1, the $(\bar{H} - \bar{K}_s)$ fluctuation colours estimated using only point source with good photometry are much redder that what is predicted given their ages and metallicities. In that case, the observed $(\bar{H} - \bar{K}_s)$ fluctuation colours for the two oldest MC superclusters are compatible with fluctuation colours predicted for much younger stellar populations, i.e., between 0.5 Gyr and 1.5 Gyr old, dominated by AGB and RGB stars. The discrepancy between observed and predicted $(\bar{H} - \bar{K}_s)$ fluctuation colour of Fornax Cluster galaxies is apparent. Fluctuation colours of a few Fornax galaxies are redder than even the reddest models, i.e., these for 500 Myr. The ages inferred for these galaxies through this procedure are much younger than the ages older than ~ 2 Gyr assigned by Kuntschner (2000). This suggests again that the single burst model is not a good representation of the star formation histories of all early-type Fornax Cluster galaxies.

The evolution of $(\bar{H} - \bar{K}_s)$ fluctuation colour versus metallicity at a fixed age is complex, and has almost no ability for stellar population age-dating. Due to the combined effects of red near-IR colours of carbon stars, and the sensitivity of carbon star formation rate to metallicity, the fluctuation colour does not simply get redder with metallicity. For 500 Myr old SSP models, $(\bar{H} - \bar{K}_s)$ gets bluer as the metallicity increases, the opposite evolution one may expect using a simple opacity argument, due to larger carbon star formation efficiency at lower metallicity. This model is significantly redder than what is predicted by González et
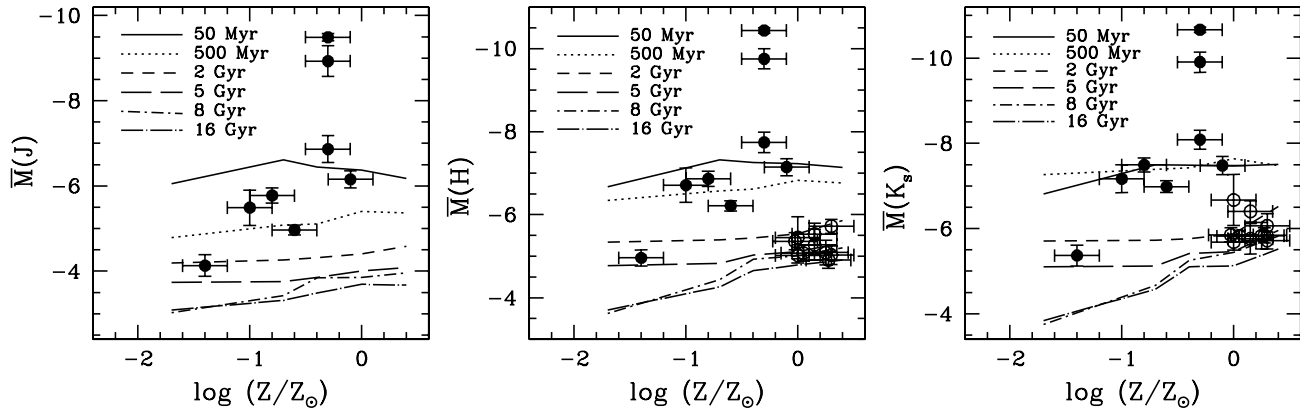

Figure 7. Comparison of near-IR fluctuation colour $(\bar{H} - \bar{K}_s)$ versus stellar population metallicity with the predictions of stellar population synthesis models. Models and symbols are akin to those in Fig. 1. All points sources with $1'$ of the superclusters' centres have been used. The grey error bars in the middle of the figure represent the Fornax cluster galaxy average.

al. (2004) based on Bruzual & Charlot (2003) isochrones, which show redder colours for more metal-rich stellar populations. This emphasises again the effects of differences in the inclusion of AGB stars in stellar population synthesis models. For SSP models where AGB stars are not fueling the near-IR SBF signal, the global trend is that young and/or metal-rich stellar populations get redder near-IR fluctuation colours than old and/or metal-poor ones.

4   SUMMARY & CONCLUSIONS

In this paper we have presented new theoretical predictions of near-IR SBFs for single age, single metallicity stellar populations. The models cover a wide range of metallicities, from 1/50 to 2.5 times solar, and ages, from 12 Myr to 16 Gyr. Our JHK SBF predictions are based on the stellar population synthesis models of Mouhcine & Lançon (2002), where late-type stellar evolutionary phases, expected to dominate the near-IR SBF signal, are included with a particular care. The stellar evolution prescriptions and stellar libraries used to calculate the stellar population isochrones benefit from an extensive comparison with various observational constraints.

The predicted SBF magnitudes and colours have been tested against observed near-IR SBFs for MC globular clusters and a sample of early-type Fornax Cluster galaxies. The data set covers large ranges of ages and metallicities. For MC superclusters younger than ~ 3 Gyr, the observed evolution

Figure 6. Comparison of *J*-band (*left*), *H*-band (*middle*), and K_s-band (*right*) SBF measurements vs. stellar population metallicity with stellar population synthesis models. All points sources with 1′ of the superclusters' centres have been used to estimate MC SBF magnitudes. Models and symbols are the same as in Fig. 1.

of near-IR fluctuation magnitudes and colours as a function of both stellar population age and metallicity are fairly well reproduced by SSP models. However, for older MC superclusters the models are not able to reproduce the observed near-IR fluctuation absolute magnitudes and colours simultaneously. The quality of the agreement between the predicted and observed near-IR brightness fluctuations depends on how the observational data are treated. The discrepancy between the predicted and observed properties of old MC superclusters is more likely due to observational reasons. Contamination by foreground sources, badly determined photometry of stars in the central, most crowded, regions, or even overexcision of these same stars could produce the recorded disagreement. It would be hence desirable to reobserve MC star clusters with SWB types VI and VII, in addition to young star clusters, in the near-IR with better spatial resolution and sky stability, in order to ascertain whether the origin of the discrepancy lies in the models or in the data. On the other hand, a few Fornax Cluster galaxies display brighter near-IR SBF magnitudes and redder fluctuation colours than what is predicted given the galaxy ages and metallicities. A possible solution of the observed discrepancy is that the single burst scenario is not accurate to model the star formation histories of these galaxies.

REFERENCES

Ajhar E. A., & Tonry J. L., 1994, ApJ, 429, 557
Ajhar E. A., Blakeslee, J.P., & Tonry J. L., 1994, AJ, 108, 2087
Bessell, M.S., Brett J.M., Scholz M., & Wood, P.R. 1989, A&AS 77, 1
Bessell, M.S., Brett, J.M., Scholz, M. & Wood, P.R. 1991, A&AS 89, 335

Blakeslee, J.P., Vazdekis, A., & Ajhar, E.A. 2001, MNRAS, 320, 193
Blöcker, T., 1995, A&A, 297, 727
Bressan, A., Fagotto, F., Bertelli, G., & Chiosi, C., 1993, A&AS, 100, 647
Bruzual, G., & Charlot, S., 2003, MNRAS, 344, 1000
Cantiello M., Raimondo G., Brocato E., & Capaccioli M., 2003, AJ, 125, 2783
Cerviño M., Valls–Gabaud D., Luridiana V., & Mas–Hesse J.M., 2002, A&A, 381, 51
Cohen J. G., 1982, ApJ, 258, 143
Elson R.A.W.,& Fall S.M., 1985, ApJ, 299, 211
Elson R.A.W.,& Fall S.M., 1988, AJ, 96, 1383
Fagotto F., Bressan A., Bertelli G., & Chiosi C., 1994a, A&AS, 104, 365
Fagotto F., Bressan A., Bertelli G., & Chiosi C., 1994b, A&AS, 105, 29
Fagotto F., Bressan A., Bertelli G., & Chiosi C., 1994c, A&AS, 105, 39
Ferrarese L. et al., 2000, ApJS, 128, 431
Ferraro F.R., Fusi Pecci F., Testa V., Greggio L., Corsi C.E., Buonanno R., Terndrup D.M., & Zinnecker H., 1995, MNRAS, 272, 391
Fluks, M.A., Plez, B., Thé, P.S., et al. 1994, A&AS, 105, 311
Frogel, J.A., Mould, J., & Blanco, V.M., 1990, ApJ, 352, 96
González R.A., Liu M.C., & Bruzual A.G., 2004, ApJ , 611, 270
González R.A., Liu M.C., & Bruzual A.G. 2005, ApJ, in press
Gautschy-Loidl R., 2001, Ph.D. Thesis, University of Vienna, Austria, Feb. 2, 2001
Iben, I., & Truran, J.W. 1978, ApJ 220, 980
Jensen, J.B., Tonry, J.L., Thompson, R.I., Ajhar, E.A., Lauer, T.R., Rieke, M.J., Postman, M., & Liu, M.C., 2001, ApJ, 550, 503
Jensen, J.B., Tonry, J.L., Barris, B.J., Thompson, R.I., Liu, M.C., Rieke, M.J., Ajhar, E.A., & Blakeslee, J.P., 2003, ApJ, 583, 712
Kuntschner, H., 1998, Ph.D. thesis, University of Durham, UK. (http://www.eso.org~hkuntsch/papers/thesis.ps.gz)
Kurucz, R.L., 1979, ApJS 40, 1
Lançon, A., & Mouhcine, M., 2002, A&A, 393, 167
Lejeune, T., Cuisinier, F., & Buser, R., 1997, A&AS, 125, 229
Lejeune, T., Cuisinier, F., & Buser, R., 1998, A&AS, 130, 65
Liu, M. C., Charlot, S., & Graham, J. R., 2000, ApJ, 543, 644
Liu, M. C., Graham, J. R., & Charlot, S., 2000, ApJ, 564, 216
Liu, M. C.,& Graham, J. R., 2001, ApJ, 557, 31
Mei, S., Quinn, P.J., & Silva, D.R. 2001, A&A, 371, 779

Table 1. Near-IR SBF predictions from new models

Z	$\log(age)$	$\bar{J}$	$\bar{H}$	$\bar{K}_s$
Z/Z$_\odot$ = 1/50	7.08	-7.541	-8.244	-8.470
	7.70	-6.047	-6.676	-6.815
	8.00	-5.460	-6.144	-6.304
	8.70	-4.788	-6.347	-7.265
	9.00	-4.715	-5.985	-6.370
	9.30	-4.192	-5.339	-5.703
	9.50	-4.031	-5.158	-5.517
	9.70	-3.734	-4.769	-5.103
	9.90	-3.022	-3.620	-3.745
	10.10	-3.046	-3.656	-3.786
	10.20	-3.077	-3.698	-3.831
Z/Z$_\odot$ = 1/5	7.08	-8.790	-9.460	-9.660
	7.70	-6.614	-7.319	-7.499
	8.00	-5.554	-6.350	-6.573
	8.70	-5.078	-6.574	-7.386
	9.00	-4.932	-6.166	-6.535
	9.30	-4.264	-5.391	-5.729
	9.50	-4.011	-5.106	-5.415
	9.70	-3.758	-4.831	-5.119
	9.90	-3.427	-4.433	-4.667
	10.10	-3.411	-4.434	-4.691
	10.20	-3.303	-4.252	-4.566
Z/Z$_\odot$ = 1/2.5	7.08	-8.869	-9.623	-9.847
	7.70	-6.444	-7.257	-7.490
	8.00	-5.428	-6.299	-6.577
	8.70	-5.110	-6.613	-7.429
	9.00	-4.683	-6.179	-7.015
	9.30	-4.311	-5.436	-5.763
	9.50	-4.104	-5.201	-5.517
	9.70	-3.854	-5.031	-5.417
	9.90	-3.840	-4.932	-5.252
	10.10	-3.631	-4.725	-5.048
	10.20	-3.479	-4.647	-5.093
Z/Z$_\odot$ = 1	7.08	-9.040	-9.740	-9.949
	7.70	-6.368	-7.231	-7.469
	8.00	-6.174	-7.469	-8.178
	8.70	-5.406	-6.828	-7.635
	9.00	-4.967	-6.345	-7.183
	9.30	-4.405	-5.535	-5.877
	9.50	-4.373	-5.552	-6.171
	9.70	-4.004	-5.114	-5.456
	9.90	-3.850	-5.010	-5.442
	10.10	-3.671	-4.771	-5.111
	10.20	-3.682	-4.777	-5.117
Z/Z$_\odot$ = 2.5	7.08	-9.012	-9.901	-10.255
	7.70	-6.174	-7.135	-7.509
	8.00	-6.122	-7.411	-8.164
	8.70	-5.367	-6.760	-7.477
	9.00	-5.037	-6.393	-7.096
	9.30	-4.582	-5.860	-6.521
	9.50	-4.314	-5.564	-6.214
	9.70	-4.087	-5.323	-5.953
	9.90	-3.960	-5.205	-5.821
	10.10	-3.817	-5.078	-5.694
	10.20	-3.662	-4.896	-5.507

Table 2. MC supercluster near-IR SBF magnitudes when all stars within 1′ from the centres of the superclusters are included.

Supercluster	$\bar{J}$	$\bar{H}$	$\bar{K}_s$
Pre-SWB	-8.93 ± 0.363	-9.753 ± 0.239	-9.905 ± 0.240
I	-9.491 ± 0.087	-10.43 ± 0.063	-10.67 ± 0.061
II	-6.865 ± 0.313	-7.743 ± 0.427	-8.087 ± 0.223
III	-6.145 ± 0.197	-7.143 ± 0.207	-7.479 ± 0.216
IV	-5.772 ± 0.178	-6.861 ± 0.183	-7.493 ± 0.166
V	-4.964 ± 0.118	-6.213 ± 0.126	-6.983 ± 0.138
VI	-5.488 ± 0.414	-6.712 ± 0.412	-7.168 ± 0.326
VII	-4.131 ± 0.252	-4.959 ± 0.192	-5.365 ± 0.245

Mouhcine, M., & Lançon, A., 2002 a, A&A, 393, 149

Mouhcine, M., 2002, A&A, 394, 125

Mouhcine, M., Lançon, A., Leitherer, C., Silva, D., & Groenewegen, M.A.T., 2002, A&A, 393, 101

Mouhcine, M., & Lançon, A., 2003, A&A, 402, 425

Persson, S. E., Aaronson, M., Cohen, J. G., Frogel, J.A., & Matthews, K., 1983, ApJ 266, 105

Renzini A., Buzzoni A., 1986, in Chiosi C., Renzini A., eds, Spectral Evolution of Galaxies, Reidel, Dordrecht, p. 195

Renzini, A., & Voli, M., 1981, A&A 94, 175

Salpeter E.E., 1955, ApJ 121, 161

Searle L., Wilkinson A., & Bagnuolo W.G., 1980, ApJ, 239, 803

Tonry, J.L., & Schneider, D.P. 1988, AJ, 96, 807

Tonry, J.L., Ajhar, E.A., & Luppino, G.A. 1990, AJ, 100, 1416

Tonry, J.L., Blakeslee, J.P., Ajhar, E.A., & Dressler A., 1997, ApJ, 475, 399

Wagenhuber, J., & Groenewegen, M.A.T., 1998, A&A, 340, 183

Westera, P., Lejeune, T., Buser, R., Cuisinier, F., & Bruzual, G., 2002, A&A, 381, 524

Worthey, G., 1994, ApJS 95, 107